MINIMIZING FIRE HAZARDS IN COAL MINES BY PROPER CIRCUIT-BREAKER PROTECTION OF 250/275-VOLT DIRECT-CURRENT SYSTEMS

BY F. J. GALLAGHER

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by

F. J. Gallagher 1/

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1/ Mining-electrical engineer, Bureau of Mines, Vincennes, Ind.

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INTRODUCTION

Some serious fires have occurred in bituminous-coal mines because of short circuits on direct-current power systems that do not have adequate circuit-breaker protection. The writer's observation of circuit-breaker installations in numerous coal mines leads to the conclusion that many persons are not properly informed as to the true functions, limitations, and operation of circuit breakers. Faulty protection results in fire hazards that endanger lives and property. Proper circuit-breaker protection would greatly minimize or, in many instances, eliminate the hazards; moreover, many operating advantages of proper application of modern circuit breakers would be gained.

The purpose of this circular is to show why fire hazards exist in many mines despite the use of circuit breakers and how the hazards may be overcome. A method is given for determining whether additional circuit-breaker protection is required for a specific 250/275-volt direct-current distribution system, and, if so, the approximate locations and capacities of the required supplemental breakers.

Tests of the effectiveness of ciruit-breaker protection were made in four coal mines. The mines were selected to illustrate both proper and improper breaker protection against short circuits. The selections were made on the basis of the theoretical application of Ohm's law, and the test results proved its practicability.

Since short circuits on the distribution system are the most common electrical fire hazard in coal mines, this discussion is confined to overcurrents arising from such short circuits. The tests and discussions are confined to 250/275-volt d. c. distribution systems.

To persons thoroughly familiar with the installation and functions of circuit breakers, this report presents nothing new. For those who have only limited knowledge of the short-circuit protection to be expected from circuit breakers, this circular should be useful. Simple fundamentals are discussed to provide information on the use of circuit breakers to prevent or minimize fires from short circuits in coal mines.

SUMMARY AND CONCLUSIONS

Results of the tests point to the necessity of adequate circuit-breaker protection on 250/275-volt d. c. systems in coal mines. The ideal setup is to provide a sectionalizing breaker for each working section or unit. Such protection generally affords suitable short-circuit protection for trailing cables of face equipment. The principal objection to the use of sectional breakers is the high initial cost. Experience has shown, however, that breaker

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protection that will isolate a section of a mine having electrical trouble but permit other sections of the mine to operate has its high cost offset by minimizing total power outages. Moreover, if mine fires can be prevented, the cost of circuit breakers may be considered low-cost insurance.

In mines with adequate circuit-breaker protection and sectionalizing, it has been definitely proved that the economic and safety aspects of such equipment warrant the investment.

ACKNOWLEDGMENT

The assistance in planning, preparing for, and making the tests and other help given by mining officials and electricians at the mines included in the report is gratefully acknowledged. The identities of the mines at which tests were conducted are concealed; they are designated by number only.

FUNCTIONS OF A CIRCUIT BREAKER

The basic function of a circuit breaker is to interrupt the flow of current when the load exceeds the safe operating current for which the system is designed. In this respect a fuse is a circuit breaker, but it has a fixed capacity and other limitations. Ordinarily a circuit breaker is considered as a device that can be set to open at a preselected current within the range of the particular breaker.

Modern circuit breakers operate under various conditions according to the service for which they are designed. All of the operating characteristics of circuit breakers are not directly applicable to fire prevention; therefore, it is appropriate to give the following summary of modern circuit-breaker functions so that their operating characteristics may be understood clearly. Circuit breakers may include the following operating characteristics:

1. Open automatically in the event of overload, short circuits, reverse current, or voltage failure.

2. Remain open a definite and adjustable time interval regardless of the cause of opening.

3. Reclose only on predetermined line conditions.

4. In closing, can be equipped to distinguish between a short circuit and load resistance of low value.

5. Equipped to "lock-out" indefinitely on a short circuit under any voltage conditions.

6. Equipped to operate on circuits that are fed from either direction.

7. Operated with a trip-free handle in emergencies.

8. Remain closed magnetically under a wide voltage range.

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9. Operate with push button or remote contol.

10. Open very rapidly and reclose quickly.

The various protective features of circuit breakers (whether used as substation breakers, tie breakers between generators, or sectionalizing stub breakers for each face unit) are accomplished by means of overcurrent, undervoltage, reverse current, voltage directional, and time-delay relays. Auxiliary relays are usually required also. To describe the funtions of all relays, resistors, and condensers used in breaker-control circuits would be inadvisable in this circular, because such information is readily obtainable in the catalogs of virtually all circuit-breaker manufacturers.

Modern circuit breakers are adjustable over a comparatively wide tripping range within 100 percent above or below their continuous current ratings. By installing proper types of breakers at proper points in the mine electrical system, the system can be sectionalized to restrict power outages to the section of a mine where a fault occurs and permit all other sections to obtain normal power requirements. Such characteristics greatly increase the value of modern circuit breakers in protecting equipment and safeguarding against fires while maintaining dependable power supply with fewest possible interruptions. Yet, in all too many mines, the potential economic advantages of proper circuit-breaker protection are virtually ignored, and many installations do not provide adequate fire protection.

The operation of a circuit breaker is as simple as one of the first lessons in electricity. It is an application of Ohm's law--I=E/R--which means that the current flowing in a given circuit depends upon the voltage impressed upon the circuit divided by the resistance of the circuit. Under normal conditions, in any circuit the maximum voltage is a fixed characteristic of a specific generator or rectifier, and the resistance is fixed by the characteristics of the conductors comprising the circuit. It follows, therefore, that the maximum current that can flow in any circuit is limited by the resistance of the circuit. When a circuit breaker is set to permit the flow of a predetermined current, any current in excess of the set value will cause the circuit breaker to open. Conversely, if an abnormal condition, such as a short circuit, occurs and the breaker does not open (assuming the breaker is in good mechanical condition), the falure to do so results from some condition that holds the current to a value below that for which the breaker is set. Usually, the cause of the current-limiting condition is excessive resistance of the circuit. One of the purposes of this circular is to explain how and why such a condition frequently exists in coal-mine distribution systems.

A second fundamental of electrical theory is that the resistance of a conductor of a given material varies directly as its length and inversely as its cross-sectional area. Simple and well known as this principle is, it apparently is ignored in many circuit-breaker installations. A circuit breaker is installed at a generator or a rectifier and set to open at a predetermined current, usually allowing for a 50-percent overload to take care of common operating-peak loads. As the distribution lines are extended, often the increase of resistance with length is not considered, and a point is reached

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where the resistance limits the current on a short circuit below the value at which the circuit breaker is set; therefore, if a short circuit occurs at a point far enough from the generator, the breaker at the generator will not open, and a fire is likely to occur.

Using these fundamentals, a group of curves (fig. 1) has been developed to represent Ohm's law graphically, using distances in feet as abscissas (horizontal) and current in amperes as ordinates (vertical). Vertically, on the left of the chart, the breaker settings for values of 100 percent overload are shown for 100-, 150-, 200-, and 300-kw. generators and are indicated by arrows pointing to the kilowatt ratings of the generators. In many instances reference to this chart will show the effectiveness of short-circuit protection quickly.

The points through which the curves are drawn are the different values of current flow that correspond to specific distances from the substation. In calculating resistance, the total length of the circuit (positive plus negative) was used. To use the graph, therefore, it is only necessary to know the one-way distance between a particular circuit breaker and any point in the distribution system.

The chart assumes that both sides of the circuit have equal current-carrying capacity, and that the total conductor capacity is uniform throughout the distance under consideration. In many instances, however, such a condition does not exist, but the chart can still be used to analyze parts of the system quickly without mathematical calculation. If conductor capacity is uniform throughout the system, it is a simple matter to select the given distance on the base line, project it vertically upward to the curve representing the conductor, which is equivalent to the total conductor capacity of one side of the given circuit, and then by horizontal projection to the left read the short-circuit current that the system will permit to flow. If such short-circuit current exceeds the breaker setting, the breaker should give adequate short-circuit protection. The process can be reversed by starting with the breaker setting and then determining the maximum distance at which a short circuit on a particular conductor will cause the breaker to open.

In using the chart where one side of the circuit has a lower current-carrying capacity than the other, it should be assumed that the entire circuit consists of the smaller conductor. In some instances the assumed circuit will carry enough current to open the breaker; that side of the circuit has greater capacity than actually is required. If the chart indicates that the assumed circuit will not permit enough current flow to open the breaker, the actual current that can flow on short circuit must be determined by calculating the combined resistance of both sides of the circuit from the particular breaker to a specific point. The method of using the chart by assuming the entire circuit to be composed of the smallest conductor in any section of the line can be tried, but it is not likely to furnish a correct value if the system extends over an appreciable distance.

The foregoing refers chiefly to main circuits. In a well-planned system, branch circuits are usually restricted in length because ordinarily the

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conductors are smaller than those of the main circuit, and the added resistance of such branch circuits often will be negligible but should not be ignored. If short-circuit current for the main circuit affecting a breaker is substantially higher than the breaker setting, the branch circuits probably can be ignored. When the short-circuit current of the main circuit approaches the breaker setting, the added resistance of the branch circuits should be considered. The role of branch circuits and other conditions discussed previously will be shown in specific examples in the discussion of the actual tests in the four coal mines.

To use the chart properly, the equivalent sizes in circular mils of copper of all conductors (including rails used as conductors) should be known. Such information is available in electrical handbooks. Resistances in ohm per 1,000 feet for various sizes of copper wire and steel rails (with equivalent copper conductor) commonly used in coal mines are given in table 1.

TABLE 1. - Unit resistances of common sizes of copper wire and steel rail

Copper Wire	
Size, cm.	Resistance, ohm/ 1,000 feet
1,500,000	0.00719
1,200,000	.00899
1,000,000	.0108
750,000	.0144
500,000	.0216
300,000	.0360
211,000	.0509

Steel Rail		
Weight/yard pounds	Equivalent each rail, cm. of copper	Resistance, ohm/1,000 feet (both rails bonded and cross bonded)
30	300,000	0.0180
40	400,000	.0135
50	500,000	.0108
60	600,000	.0090
70	700,000	.0077
80	800,000	.0067
90	900,000	.0060
100	1,000,000	.0054

When two or more conductors are connected in parallel to form one side of a circuit, the total circular-mil copper equivalent is found by adding the copper equivalents of all conductors used in that side. Thus two 60-pound steel rails, connected to the circuit, are equivalent to 1,200,000 cm. of copper. One 60-pound steel rail and a 500,000 cm. negative feeder are equivalent to 1,100,000 cm. of copper wire. Such a size is not shown on the chart, but values for it can be interpolated accurately enough between the 1,000,000 and 1,200,000 cm. curves. Similarly, any group of different size conductors can be combined, and if the total in circular mils is not shown on the chart the next lower-size conductor can be used or values for the combination determined by interpolation.

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SUBSTATIONS IN PARALLEL

When several substations are operated in parallel, apparently some think that a circuit breaker at each substation give adequate protection against short circuits. This is true only if the distribution system is properly laid out with due regard for lengths and sizes of conductors. Otherwise, one or more conversion units relatively close to the short circuit may go off the line, but one or more units at greater distances may stay on the line and continue to feed current through the short circuit.

Where two or more substations are operated in parallel, short-circuit protection is determined by considering each substation separately, using the chart (fig. 1) to determine if any part of the distribution system extends beyond the greatest distance at which the breaker at that particular substation will function on short circuit. The method of making such determinations is described for the four mines in which actual tests were made of circuit-breaker protection for 250/275-volt d. c. systems.

TEST CONDITIONS AND RESULTS

Mine 1

The 250/275-volt d. c. is supplied from a 200-kilowatt motor-generator set installed on the surface near the slope mouth and two 300-kilowatt rectifiers underground, all connected to operate in parallel. The alternating current supplied to the rectifiers and the motor of the motor-generator set is at 2,300 volts. Each rectifier is installed near a borehole through which the 2,300-volt a.c. supply enters the mine. The cables for this current are the only source of 2,300-volt a.c. power in the mine. An oil circuit breaker and a manually operated disconnecting switch are installed at the bottom of each borehole.

Figure 2 is a skeleton lay-out of the direct-current distribution system in mine no. 1 and shows the capacities of the generator and rectifiers, size of feeders, both positive and negative, approximate average load on each set, and current values at which the circuit breakers are set to trip.

Note: Except where additional copper is shown in figures 2-6, inclusive, the return circuit consists of 60-pound rail for main track and 40-pound rail for track in producing sections.

The generator on the surface assists in supplying power for the haulage load between the slope bottom and the rectifier at 1 and 2 east, 12 north, a distance of 4,900 feet. The second rectifier is installed at 3 and 4 west, 12 north, 1,000 feet north of the first rectifier; both are located so as to furnish power to both haulage and face loads.

Some recorded load tests were conducted on the rectifiers for the operator's information and disclosed that the average load on each set was approximately 900 amperes. Peaks of 1,000 to 1,400 amperes were recorded, but these were infrequent; consequently, the load factor is quite small.

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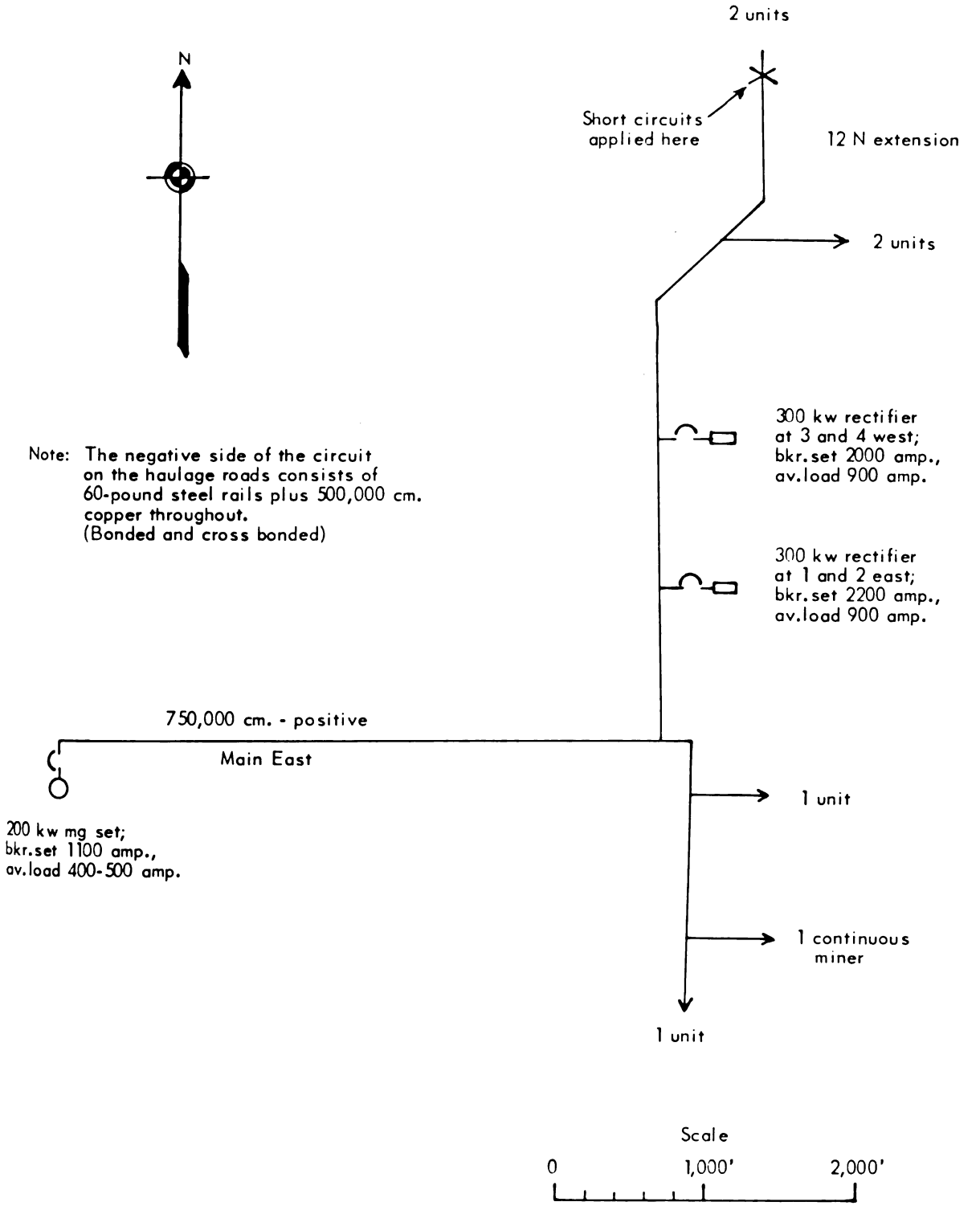
2 units
N
Short circuits applied here
12 N extension
2 units
300 kw rectifier at 3 and 4 west; bkr.set 2000 amp., av.load 900 amp.
Note: The negative side of the circuit on the haulage roads consists of 60-pound steel rails plus 500,000 cm. copper throughout. (Bonded and cross bonded)
300 kw rectifier at 1 and 2 east; bkr.set 2200 amp., av.load 900 amp.
750,000 cm. - positive
Main East
1 unit
200 kw mg set; bkr.set 1100 amp., av.load 400-500 amp.
1 continuous miner
1 unit
Scale
0
1,000'
2,000'

Figure 2. - Skeleton lay-out of 250/275-volt d.c. distribution system, mine 1.

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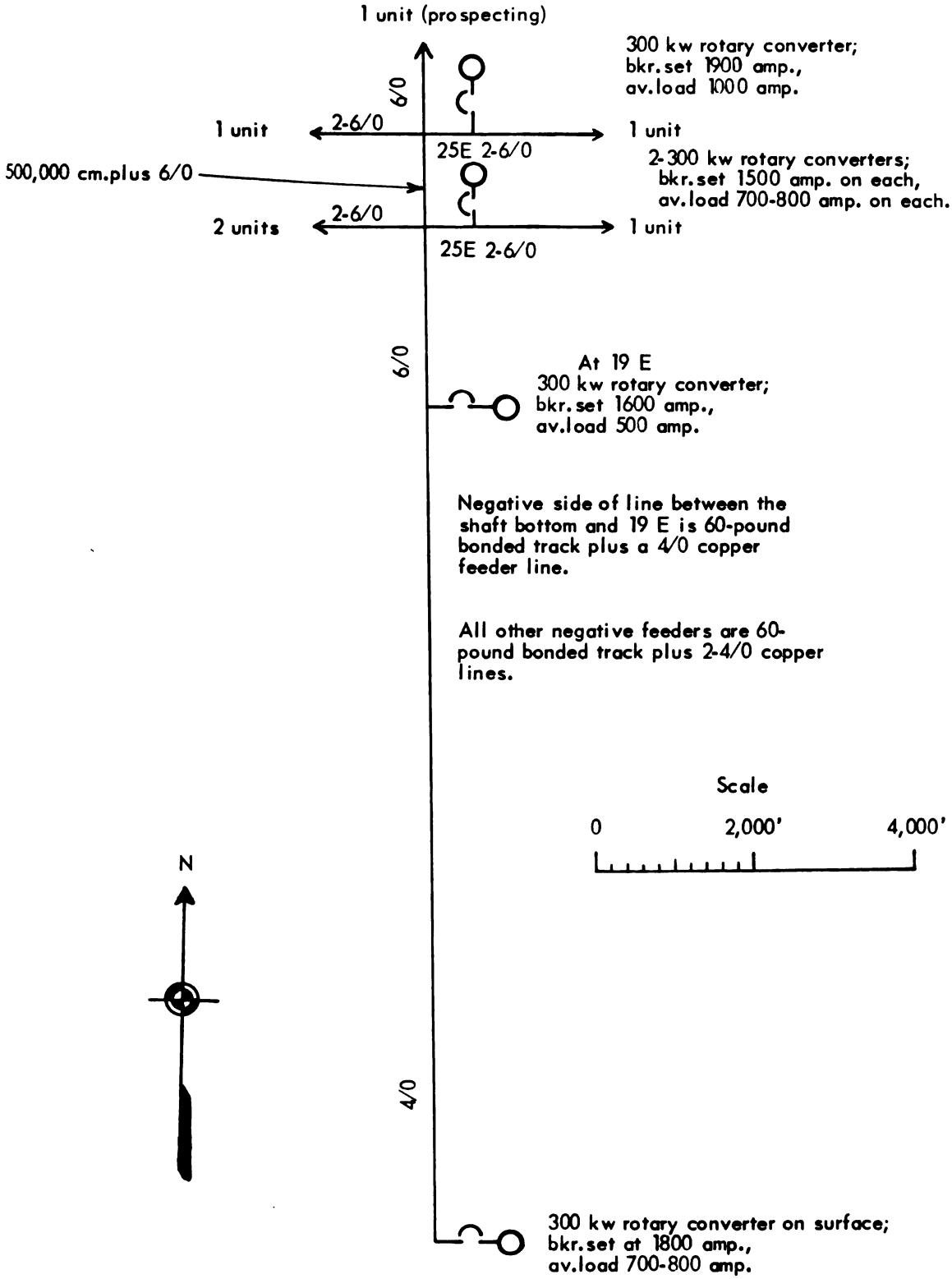

Figure 3. - Skeleton lay-out of 250/275-volt d.c. distribution system, mine 2.

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The chart (fig. 1) indicates that short-circuit protection from any point in the distribution system to each rectifier is adequate.

In this instance, each face unit consisted of a cutting machine, loading machine, two storage-battery shuttle cars, and an electric drill. Trailing cables were equipped with fuse protection, and machines were protected by individual circuit breakers. The equipment was the trankless type, and face loads were carried by postive and negative 500,000 cm. copper feeders except the feeder circuit for the continuous miner, which consisted of 750,000 cm. conductors. Branch feeders were not extended more than 1,200 feet from the main circuit on the track haulageway in this mine; therefore the added circuit resistances of 0.05 ohm for the 500,000 cm. feeders and 0.03 ohm for the 750,000 cm. continuous-miner feeders may be disregarded.

According to the chart and the calculations, the line resistances were substantially less than those that would limit the current flow below the respective breaker settings. To determine if this were true in practice, a number of short circuits were created at the end of the main line in 12 north extension, which was farthest from any substation. All load was cut off, and only the 200-kilowatt surface generator supplied power to the 9,000-foot circuit. The breaker setting on this generator, normally 1,100 amperes, was raised in stages to 1,600 amperes. In each instance, the breaker opened instantly when a short circuit was established between the trolley wire and the track at the far end of the circuit.

Evidently the possibility of mine fires from short circuits on the direct-current system in this mine are remote.

Mine 2

The power supply for the 250/275-volt d. c. system was from five 300-kilowatt rotary converters, operated in parallel. The 2,300-volt a.c. supply to the converters entered the mine through boreholes and was reduced to the necessary alternating-current values for the various sets through transformer banks in the substations. This was the only 2,300-volt power used underground. Oil circuit breakers were installed at the bottoms of the boreholes in addition to manually operated disconnecting switches.

Figure 3 shows the lay-out of the system with the various sizes of feeders, average load on each set, and circuit-breaker over-current trip settings.

According to the calculations, the resistance of the circuit between the shaft bottom and 19 east was such that the current flow on the occurrence of a short circuit would be limited to a value below the breaker setting on either the converter on the surface or the one at 19 east, depending upon where the short circuits occurred between the two. Several short circuits were created along the haulage road between the shaft bottom and 19 east to prove that this was true in practice. For the tests, the converter on the surface was shut down, because the first test was made near the shaft bottom, and the breaker on the surface opened.

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The test procedure was as follows: One man was stationed at 19 east substation to close the line switch when short circuits were applied and to trip the breaker as quickly as possible after a current reading was taken from the switchboard ammeter. A piece of 4/0 trolley wire was used to create the short circuit between the trolley wire and track. Some resistance occurred at the points of a short circuit because in each instance the wire merely was placed on the track and held by a small piece of rock. Sputtering also occurred with each test when the switch was closed.

The following table shows the distances from 19 east substation and the current flow for each test:

Test	Distance from 19 E Substation, feet	Current flow, amperes
1	8,000	600
2	7,000	750
3	5,000	1,100
4	4,000	Breaker opened

Test 1 was made approximately 1,000 feet north of the shaft bottom, and the results indicate that a short circuit occurring between the shaft bottom and 19 east would permit either the converter on the surface or the one in 19 east to remain on the line and feed current through the short circuit, which might cause a fire at any point along 9,000 feet of haulage road.

The author pointed out to the chief electrician that unless more copper was added to the circuit a 600-ampere tie breaker installed midway between the two sets would be required to provide the necessary protection. Such tie breakers can be adjusted to meet necessary line requirements; a nominal 600-ampere tie breaker can be set for current values between 200 and 1,200 amperes.

It also was pointed out that if the 4/0 feeder, used in conjunction with the track on the negative side of the circuit, was installed to supplement the trolley wire on the positive side, the voltage drop on the positive side would be reduced by one-half, and that the 60-pound bonded and cross-bonded track had approximately three times the current-carrying capacity of two 4/0 wires. For example, if a load of 500 amperes was drawn 4,000 feet from the 19 east generator through the 4/0 trolley wire, inasmuch as the resistance of 4,000 feet of 4/0 wire is approximately 0.2 ohm, the voltage drop (RI) would be 500 amperes multiplied by 0.2 ohm, or 100 volts.

Calculations revealed that circuit-breaker protection beyond 19 east was adequate; consequently, no tests were run in this part of the mine. With the present set-up, if a short circuit should occur beyond 19 east, the converter on the surface would continue to feed the circuit and possibly start a fire; however, if protection was provided between 19 east and the shaft bottom, the possibility of a mine fire from short circuits would be reduced considerably.

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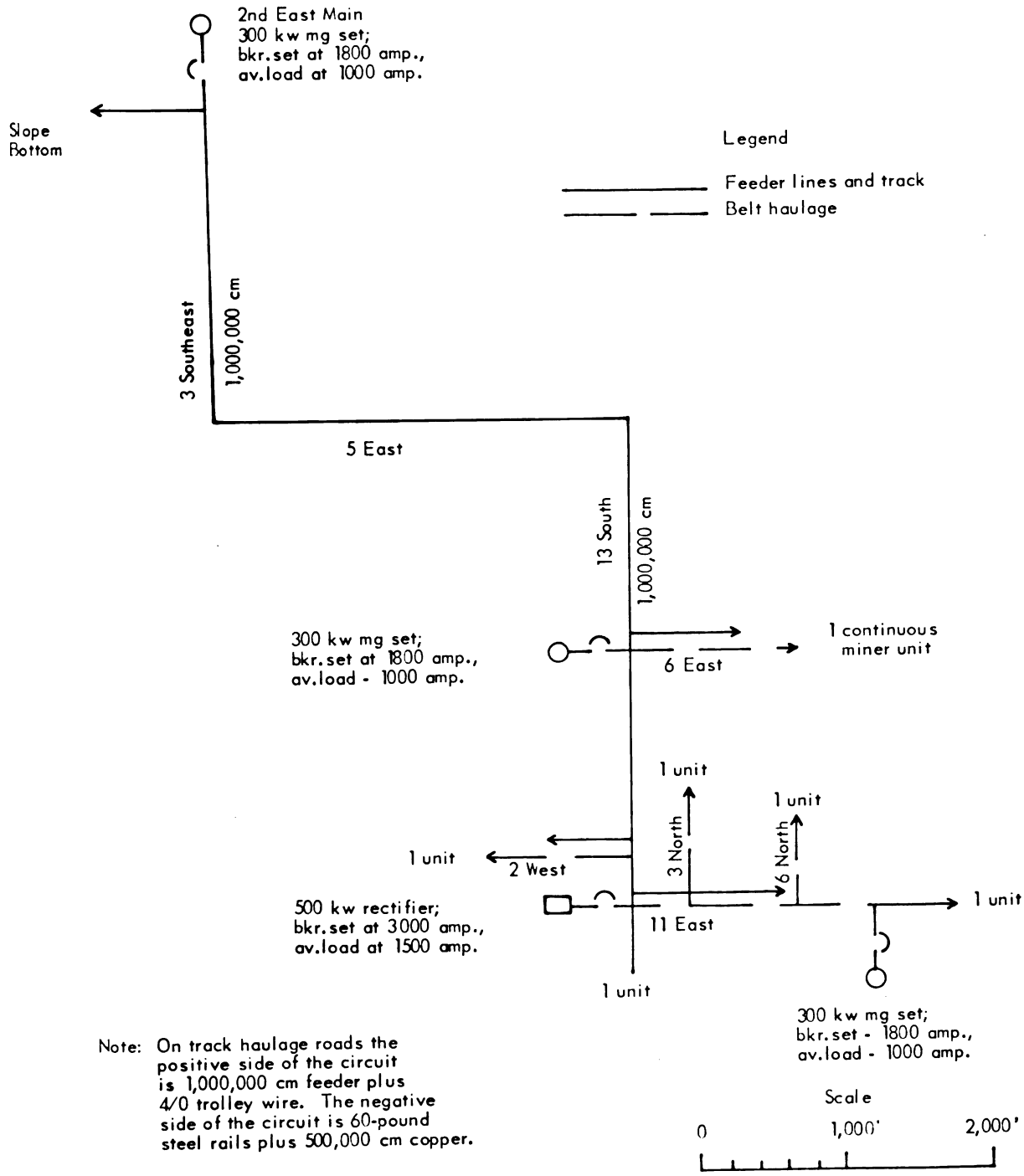

Figure 4. - Skeleton lay-out of feeder lines, track, and belt haulage, mine 3.

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Mine 3

Direct-current power is supplied by three 300-kilowatt motor-generator sets and one 500-kilowatt rectifier all installed underground in well-ventilated concrete-block rooms. The units operate in parallel and are equipped with load distributors. The generators are driven by 2,300-volt synchronous motors and the alternating-current supply to the rectifier is 2,300 volts also. All conversion units are installed in the immediate vicinity of boreholes, and no extensive runs of 2,300 volt cables are required underground.

Figure 4 shows the lay-out of the system, size of feeder lines, average load on each conversion unit, and settings of the circuit breakers. Each face unit consists of a rubber-tire-mounted mining machine, tractor-mounted loading machine, and two shuttle cars.

One point at which a short circuit on the direct-current system would be most likely to start a fire is at the end of the feeder line and tract at the 5 north entry off 11 east. This is the farthest point from the generator between 1 and 2 east main entries near 3 southeast entry, a distance of approximately 10,000 feet. A short circuit on the direct-current system at this point would be one of the most severe that could occur. The positive side of the circuit consists of 1,000,000 cm. feeder and 4/0 trolley wire--a total of 1,200,000 cm. of copper, which has a resistance of 0.009 ohm per thousand feet. The total resistance of 10,000 feet of the positive side of the circuit is 0.09 ohm. The negative side of the circuit consisting of 60-pound bonded and cross-bonded track and a 500,000 cm. feeder is the equivalent of 1,700,000 cm. copper and has a resistance of 0.006 ohm per thousand feet. The total resistance of the negative side of the 10,000-foot circuit is 0.06 ohm. The 60-pound track is considered to have the carrying capacity of 1,200,000 cm. copper. The total resistance of the entire circuit is then 0.09 ohm plus 0.06 ohm or 0.15 ohm. The amount of current that could flow on short circuit at the farthest point from a generator is 275 volts divided by 0.15 ohm or 1,833 amperes. Even when no other load is on the system, a short circuit at the farthest point from a generator would cause the breaker to open because the breakers are set to trip instantaneously at 1,800 amperes, and the 300-kilowatt generators generally carry an average load of 1,000 amperes during normal operation. The additional current demand caused by a short circuit on the system probably would open the breaker, and the possibility of causing a fire from short circuits on the direct-current system would be reduced considerably.

It was mentioned previously, however, that 1,833 amperes would flow on short circuit and the breaker was set to open at 1,800 amperes, but if poor bonding or loose joints were in the circuit, they would increase its resistance, limit the value of the current to a point below 1,800 amperes, and the breaker would not open. Furthermore, this illustrates the importance of good bonding and track maintenance in the prevention of fires from short circuits. This discussion assumes that no load other than the short circuit existed on the system.

Furthermore, if a short circuit should occur near the slope bottom on the 3 southeast entry, the breaker on the rectifier at 11 east, 13 south would

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not open, and a fire could start from this source. The resistance of the circuit from the rectifier toward the slope bottom for each 1,000 feet is the same as aforementioned or 0.009 ohms (positive) plus 0.006 ohms (negative), which equals 0.015 ohms. The greatest resistance that could exist in the circuit and permit enough current to flow to open the circuit breaker on the rectifier would be (R= E) 275 volts divided by 3,000 amperes (circuit-breaker setting) or 0.091 ohms.T) Since the resistance of the circuit is 0.015 ohms per thousand feet, the distance limit at which the breaker on the rectifier would open would be 0.091 ohms (maximum resistance) divided by 0.015 ohms or 6.0 x 1,000, which equals 6,000 feet. It is indicated that a short circuit occurring between the slope bottom and approximately 4,000 feet toward the rectifier could start a fire. In order to provide a safety factor, a tie breaker should be installed about midway between the 1 and 2 east substations, and the rectifier would probably provide the necessary protection.

Mine 4.

The 250/275-volt d.c. power was supplied by two 150-kilowatt motor-generator sets, one 500-kilowatt rectifier, and one 300-kilowatt rectifier all installed underground, and one 300-kilowatt motor-generator set which was installed on the surface.

The direct-current circuit line from the generator on the surface enters the mine through a borehole near the shaft; it consists of two 500,000 cm. cables.

The direct-current line extending south from the shaft to 15 east, 17 east, and 17 west consists of a 4/0 solid-copper wire and a 6/0 trolley wire. Extending north from the shaft to 17 and 20 south entries off 18 east, the direct-current feeder lines consist of two 4/0 solid-copper lines supplemented by a 6/0 trolley wire.

Figures 5 (south side) and 6 (north side) show the location of substations, size of feeders, average load on each station, and settings on the overcurrent trips on station breakers.

From the west side of the rectifier in 15 east, about 500 feet of 1,000,000 cm. copper feeder has been installed, and a 500,000 cm. feeder line has been installed from the rectifier to the working sections in 15 east.

The main-line track consists of 60-pound rails well bonded and cross-bonded. Forty-pound rails are used in the working sections.

The resistance (positive and negative) of 1,000 feet of circuit north of the shaft on the main line is 0.0233 ohm. The breaker on the generator at the surface is set to trip at 1,400 amperes. The limit of line resistance that would permit the breaker to open in the present set-up is 0.2 ohm. Inasmuch as 1,000 feet of circuit north of the shaft has a resistance of 0.0233 ohm, the maximum distance north of the shaft at which a short circuit on the system would trip the surface breaker would be 0.2 divided by 0.0233 multiplied by 1,000 or approximately 8,600 feet. A short circuit beyond this point would

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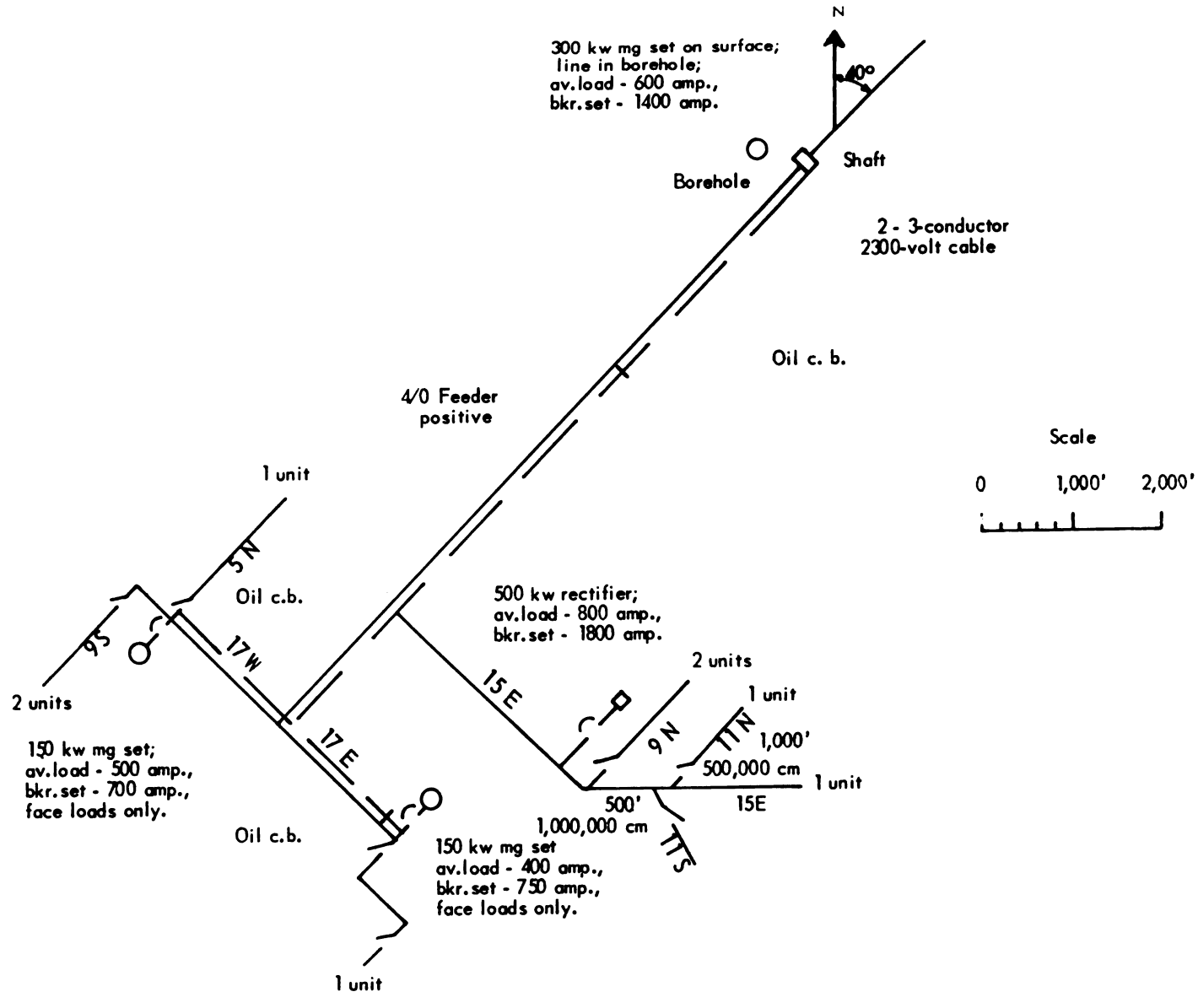

Figure 5. - Skeleton lay-out of 2,300-volt a.c. and 250/275-volt d.c. distribution system, south side of mine 4.

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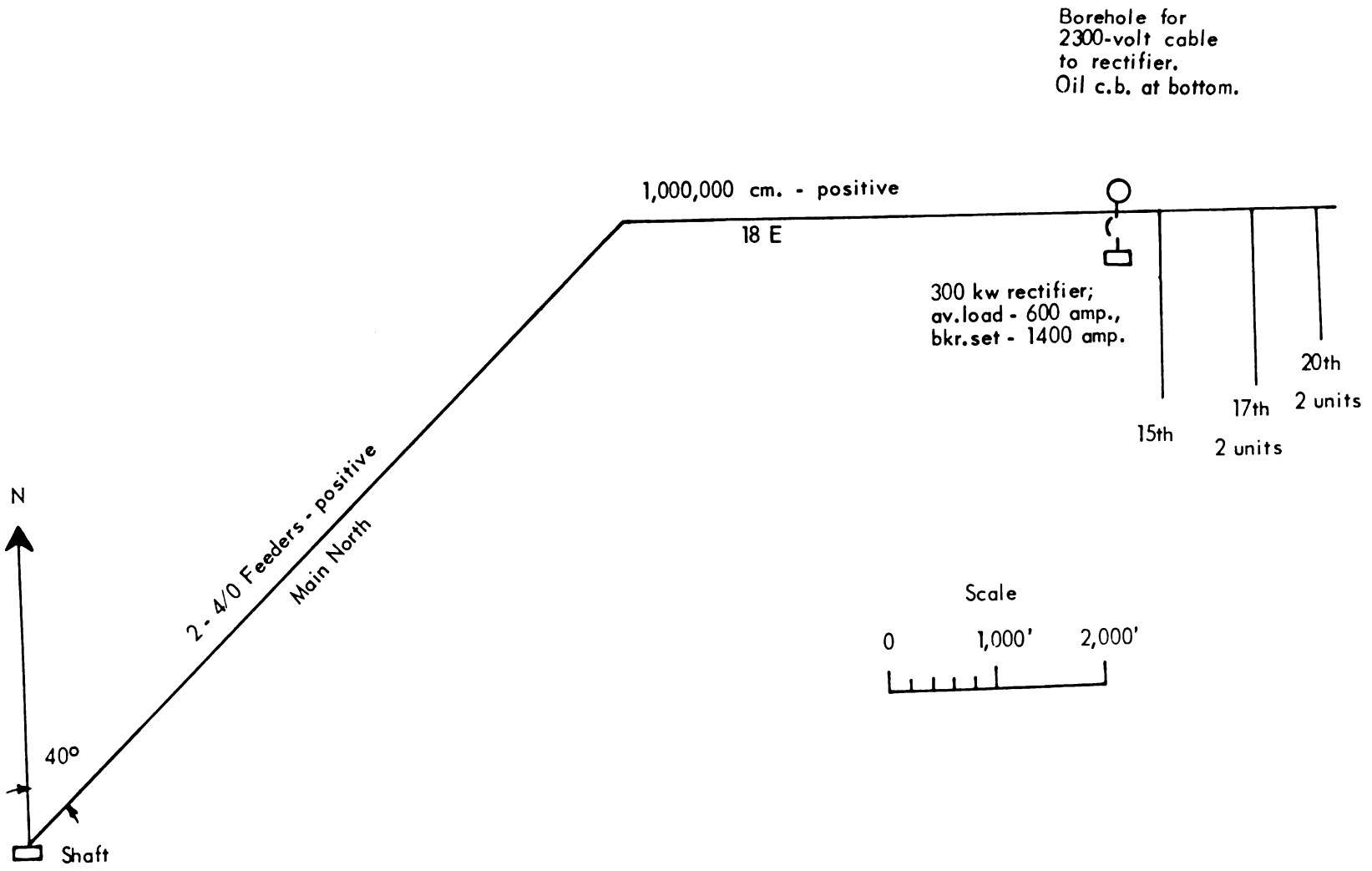

Figure 6. - Skeleton lay-out of 2,300-volt a.c. and 250/275-volt d.c. distribution system, north side of mine 4.

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permit the motor-generator set on the surface to remain on the line and supply current through the short, possibly starting a fire.

From the rectifier in 18 east to the junction with the main north (fig. 6), the resistance of the 4,800 foot circuit was 0.086 ohm. The limit of line resistance that would permit enough current to flow to open the breaker on this rectifier was 0.2 ohm; therefore, from the junction of main north and 18 east, the line resistance at which the breaker would open was 0.2 ohm minus 0.086 ohm, or 0.114 ohm. The resistance per thousand feet of circuit on the main north as in the preceding paragraph was 0.0233 ohm; therefore, the distance along the main north toward the shaft bottom that the breaker on the rectifier in 18 east would open is 0.114 divided by 0.0233 multiplied by 1,000 or approximately 4,900 feet from the junction of 18 east a total distance of 8,800 feet (4,000 feet + 4,800 feet) from the 18 east rectifier.

On the south side of the shaft (fig. 5) the resistance of 1,000 feet of circuit is 0.0324 ohm. The limit of line resistance at which the breaker in the surface substation would open is 0.2 ohm; therefore, 0.2 divided by 0.0324 multiplied by 1,000 is approximately 6,000 feet--the maximum distance south of the shaft at which a short circuit would open the breaker in the surface substation.

By similar calculations it was determined that the breaker on the 500-kilowatt rectifier in 15 east set at 1,800 amperes would open on short circuit at a limit of 2,800 feet north of 15 east on main south. It also was determined that this breaker would open when a short circuit occurred about 1,000 feet east and 800 feet west of main south in 17 east and 17 west entries, respectively.

The conclusion is that in this mine a short circuit on the direct-current system cannot occur that will disconnect all generators from the line; consequently, a short circuit at any point on the system presents the possibility of a mine fire.

To avert or minimize the possibility of mine fire owing to a short circuit on the direct-current distribution system, tie breakers should be installed according to the following recommendation. The breakers, 1,000-ampere capacity, are adjustable and can be set to open at load currents of 500 to 2,000 amperes. One breaker should be installed near the junction of 17 east and 17 west off main south, a second breaker about 4,000 feet north of 17 east and 17 west on main south, and a third breaker approximately 5,200 feet north of the main shaft on main north entry. These locations were selected from line resistance, substation capacities, and limits of distance along the line at which substation breakers would open on short circuit, as described in the foregoing. The circuit breakers at the proposed locations would greatly minimize the possibility of fire owing to a short circuit on the direct-current distribution system in this mine.

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